



Ablator response model development: from flight data back to fundamental experiments

N. N. Mansour

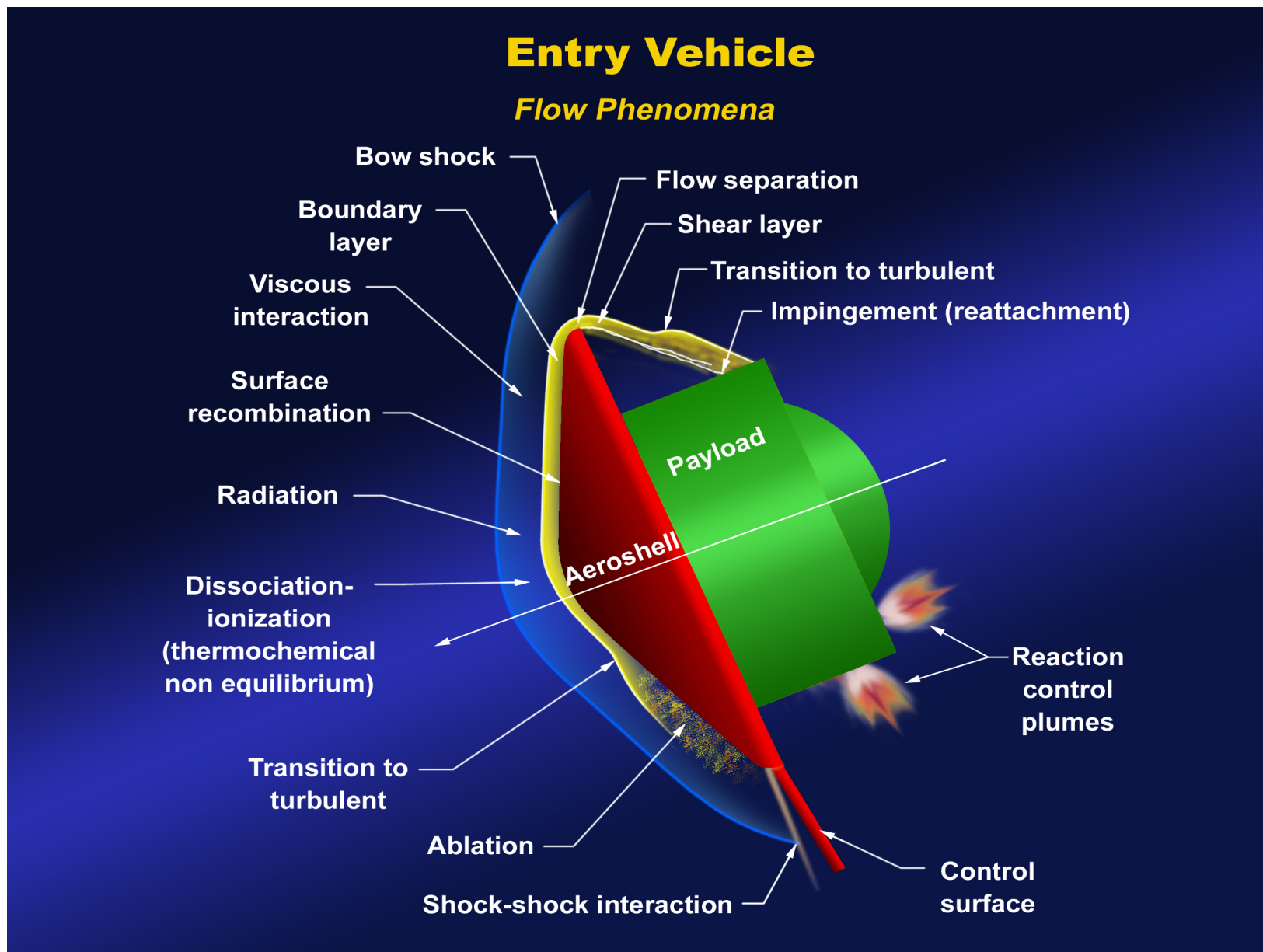
NASA Ames Research Center

and

J. R. Lachaud

UCSC

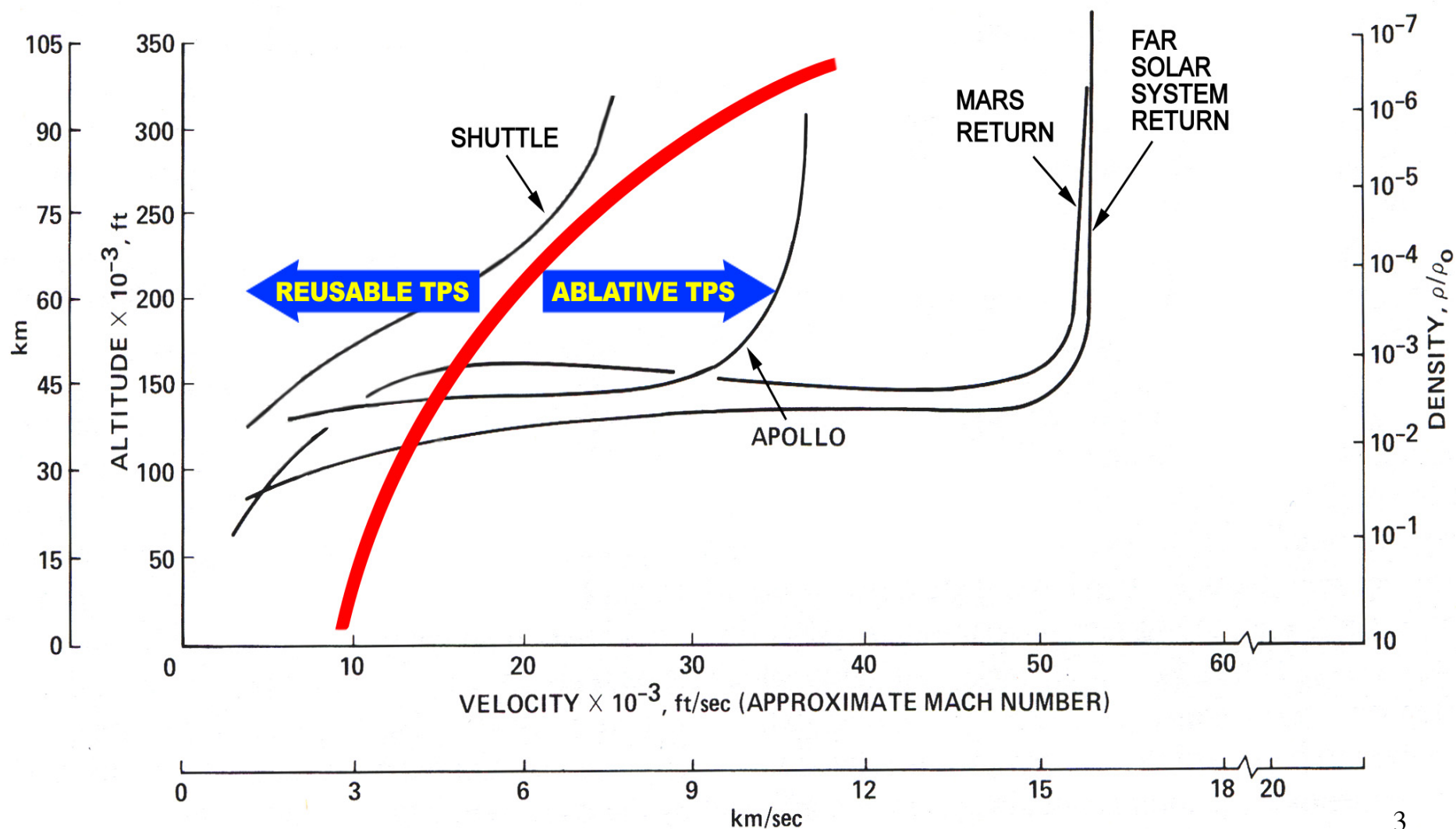
Needs for Thermal Protection Systems (TPS)





TPS Systems

Two types of TPS materials





NASA - Space Exploration

Current thinking

- Low Earth Orbits (LEO) – Private providers
- Beyond LEO – Both Private & NASA providers
 - Ablators will play a major role in NASA's atmospheric entry missions



Phenolic Impregnated Carbon Ablator (PICA)

Carbon-Phenolic class of ablators

PICA: member of the family of Lightweight Carbon Ablators (LCAs) that was developed at NASA Ames Research Center as a lightweight thermal protection system (TPS) material for the Stardust mission



+



=



carbon Fiberform™

resin

Widely used class of materials

- ✓ Stardust
- ✓ MSL
- ✓ Dragon
- ✓ AQ61
- ✓ ...

Excellent Performance:
[250 W/cm² to 1100 W/cm²]



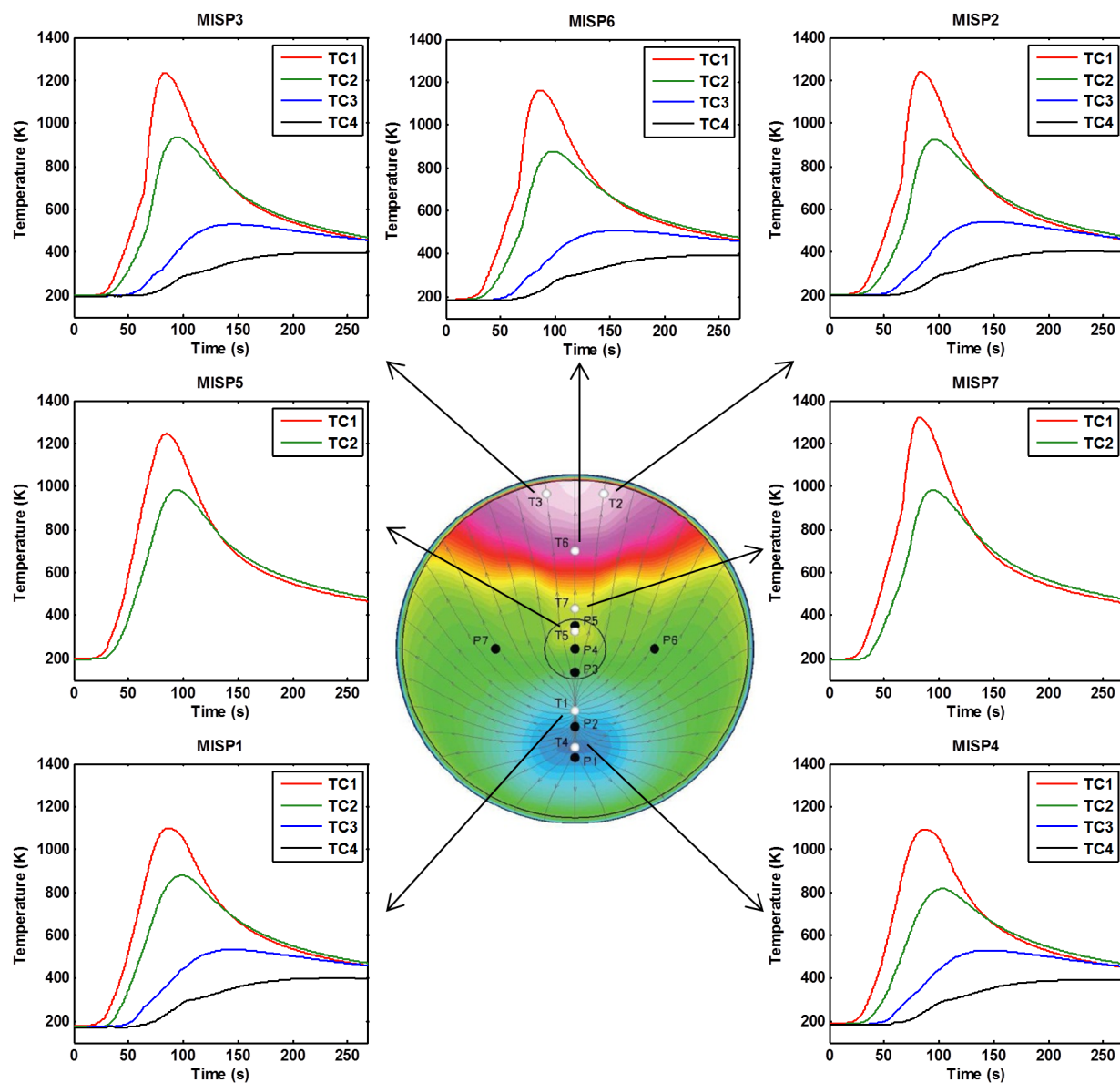
Mars Science Laboratory (MSL) heatshield



Dragon capsule, SpaceX



Flight data: MEDLI



Mahzari et al.
AIAA 2013-0185



Flight data: MEDLI

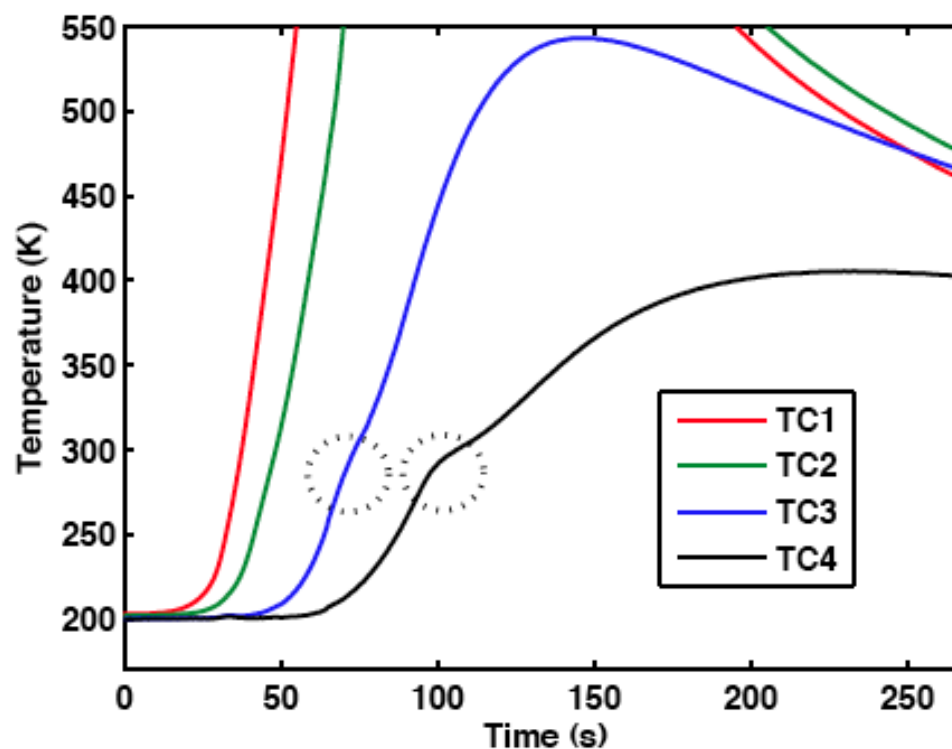


Figure 4. The “hump” observed in TC3 and TC4 data for plug 2 (seen also for other plugs).



Performance of Current State Of the Art

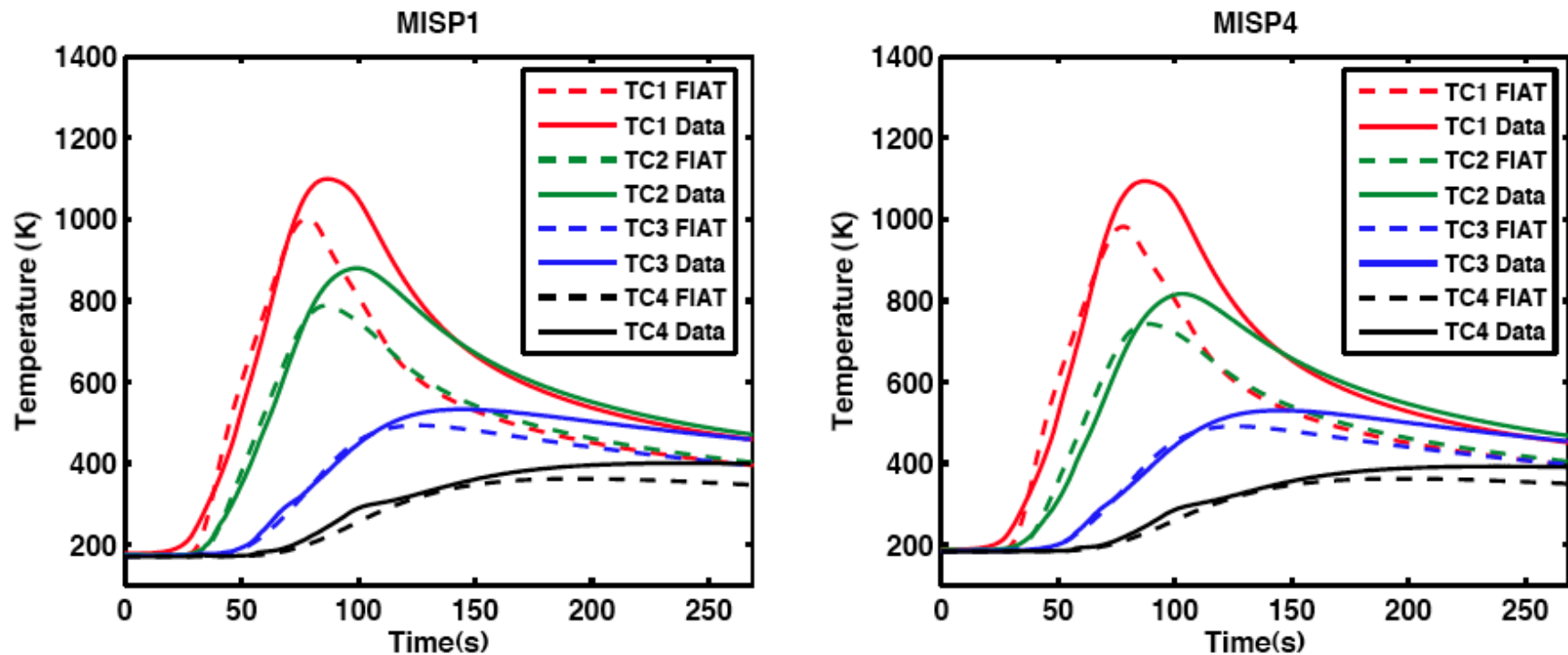


Figure 8. FIAT predictions compared with flight data for plugs 1 and 4.



Performance of Current State Of the Art

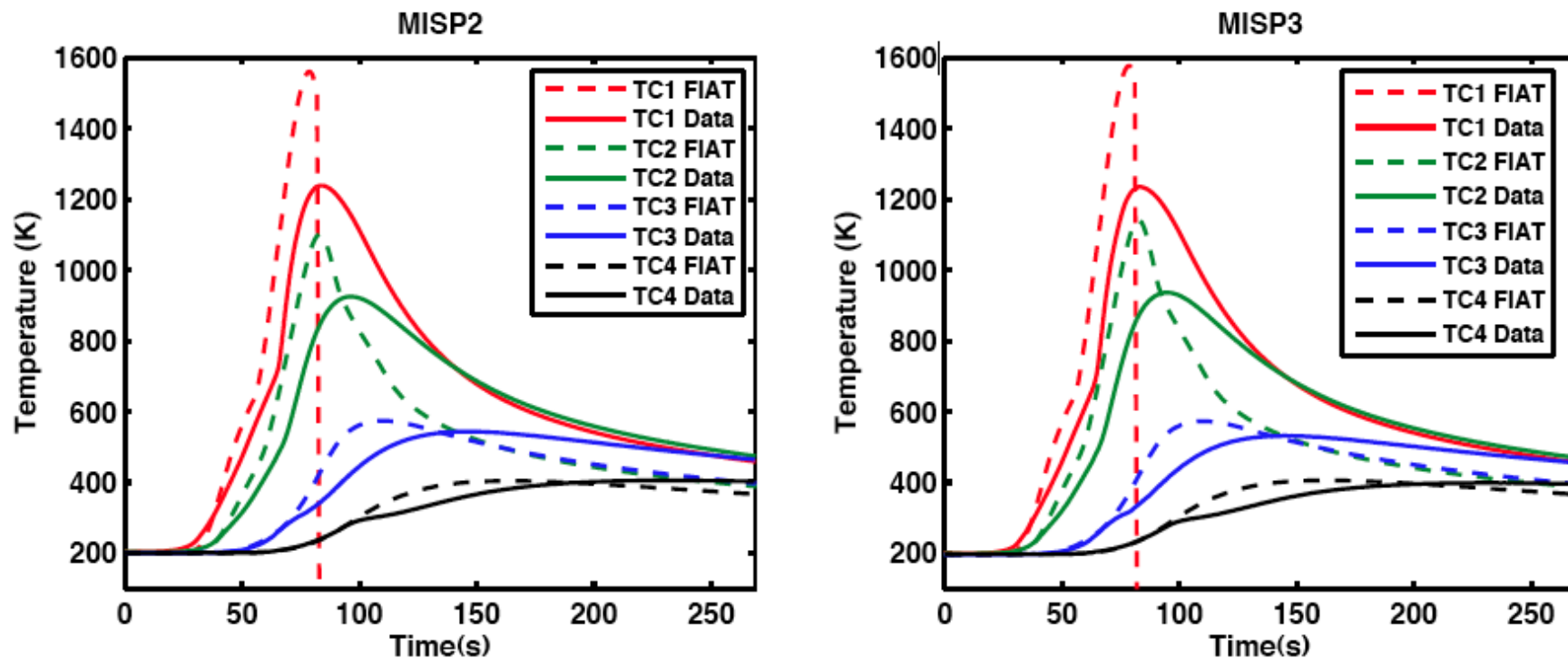


Figure 9. FIAT predictions compared with flight data for plugs 2 and 3.



AN ANALYSIS OF THE COUPLED CHEMICALLY REACTING BOUNDARY LAYER AND CHARRING ABLATOR

Part I

Summary Report

By Robert M. Kendall, Eugene P. Bartlett,
Roald A. Rindal, and Carl B. Moyer

6.3.3 Additions to the Physical Model

Since the CMA in-depth computation includes only the physics of the basic pyrolysis problem, specific materials with important additional subsurface events are not all well described by the program. Physical events here include coking and subsurface char erosion due to interaction with the pyrolysis gas, chemical kinetics of pyrolysis-gas cracking reactions as the gas flows through the char, thick liquid layer run-off (the present chemical programs account for only thin, nonviscous liquid-layer removal), additional subsurface chemical reactions such as carbon-silica reactions, thermal expansion effects, and mechanical damage to weak chars.

For sale by the Clearinghouse for Federal Scientific and Technical Information
Springfield, Virginia 22151 - CFSTI price \$3.00



. Context

Today's standpoint (2008)

46th AIAA Aerospace Sciences Meeting and Exhibit
7 - 10 January 2008, Reno, Nevada

AIAA 2008-1202

Post-Flight Evaluation of Stardust Sample Return Capsule Forebody Heatshield Material

Mairead Stackpoole^{*}, Steve Sepka[†] and Ioana Cozmuta[‡]
ELORET Corporation, Sunnyvale, CA, 94086

Dean Kontinos[§]
Ames Research Center, Moffett Field, CA, 94035

Phenolic Impregnated Carbon Ablator (PICA) was developed at NASA Ames Research

For the near stagnation core, the model over predicts recession by 61 percent. For the flank core, the difference in the predicted recession values is 25 percent. The discrepancies at the flank core are of the same order as differences between calculation and arc-jet tests against which the model was calibrated.⁵ The over-prediction at the near-stagnation core is not fully understood.

strength assessment of remaining virgin PICA, an emissivity profile, a chemical analysis profile, and a microstructural analysis. Results show good agreement in comparisons of

Have we reached the limitations of Kendall's model (used in current codes)?

and the only degradation observed was that caused by heating on entry. A substantial amount of virgin PICA was present in all cores examined.



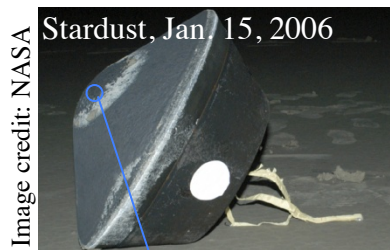
Need: understand then build phenomenological models

Steps	Methods
• Improve global understanding • Determine the important phenomena • Derive phenomenological models • Validate • Couple to environment • 3D design (gap, holes, etc.)	→ Revisit the physics → Analysis of the orders of magnitude → Multiscale approach (micro-to-macro) → Experiments on laboratory material → Development of 3D simulation tool → Development of coupling tools (multi-physics)

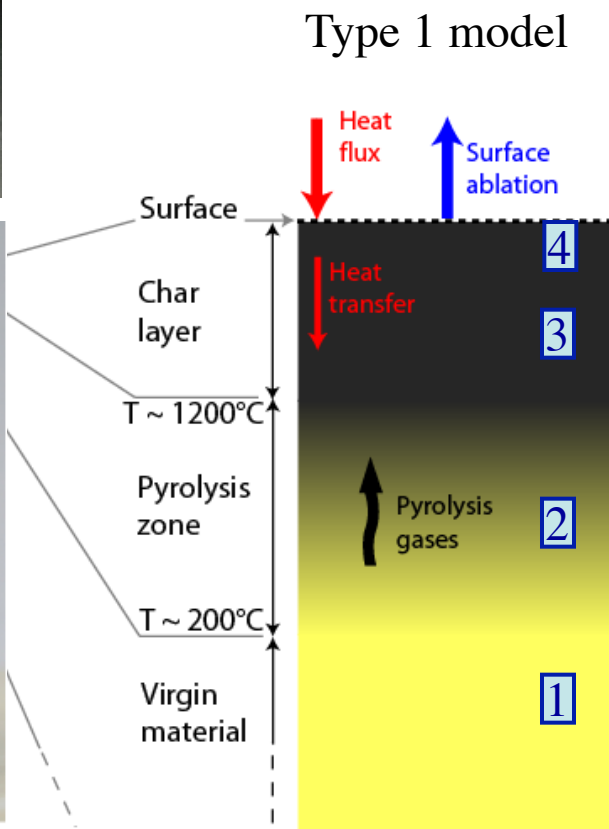
Keep the study as general as possible, but the physics changes from one material to another, and from one atmospheric re-entry to another.



Physics and Chemistry in Ablative Materials



Core - Stardust TPS⁽¹⁾



4 - Partially ablated

Towards “High-Fidelity Model”

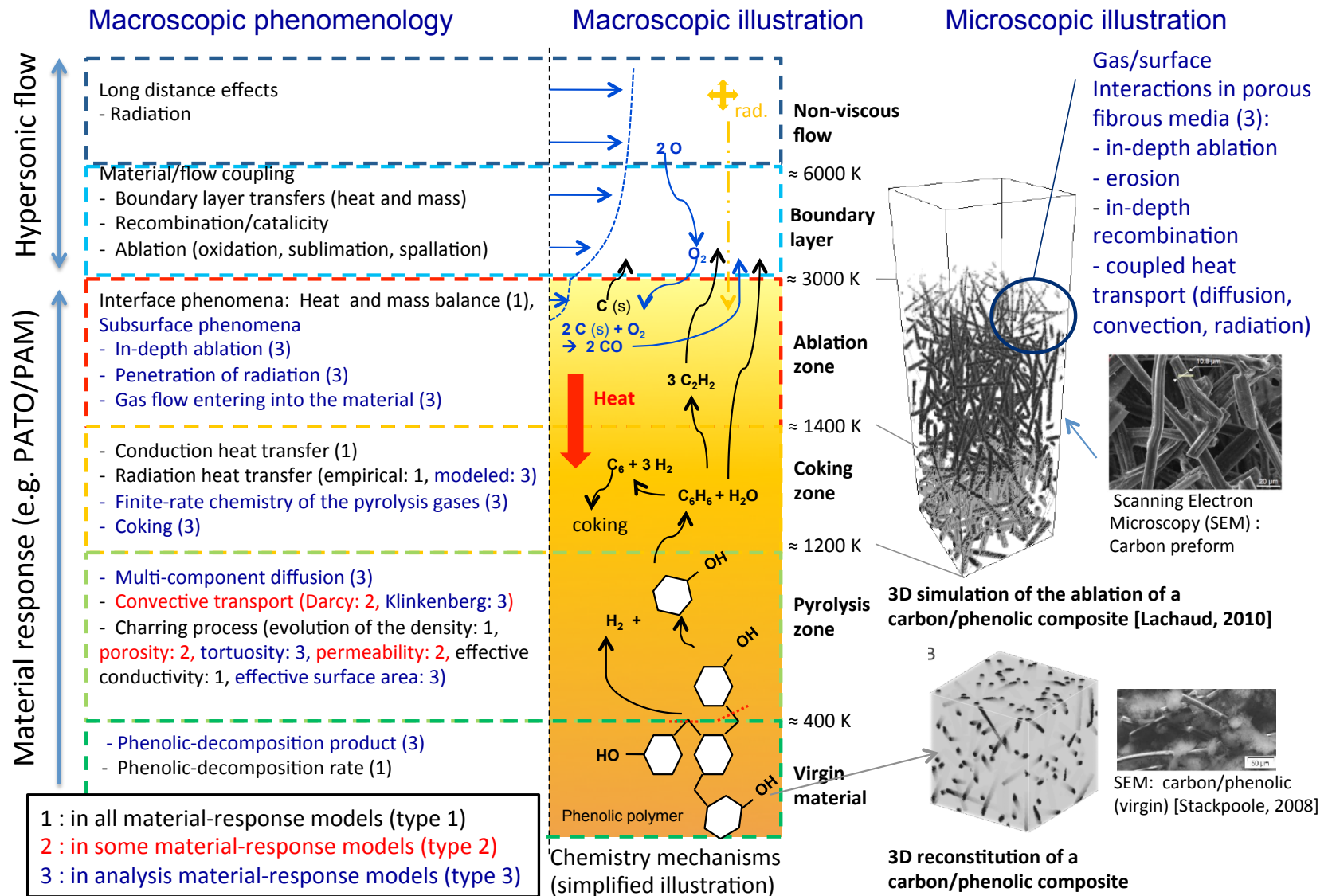
- **Type 1:** Heat transfer, pyrolysis, simplified transport of the pyrolysis gases, equilibrium chemistry, surface ablation (current state-of-the-art)
- **Type 2:** Type 1 augmented with an averaged momentum equation for the transport of the pyrolysis gases
- **Type 3:** High-fidelity model (**Type 2** + finite-rate chemistry, multi-component diffusion, in-depth ablation/coking, explicit radiative transfer model, ...)



SEM micrographs⁽¹⁾

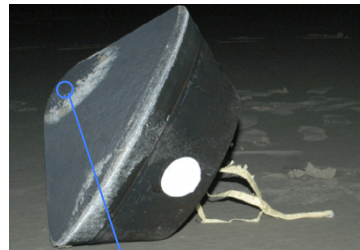
[1] M. Stackpoole *et al.*, Post-Flight Evaluation of Stardust Sample Return Capsule Forebody Heatshield Material, AIAA 2008-1202

Phenomenology

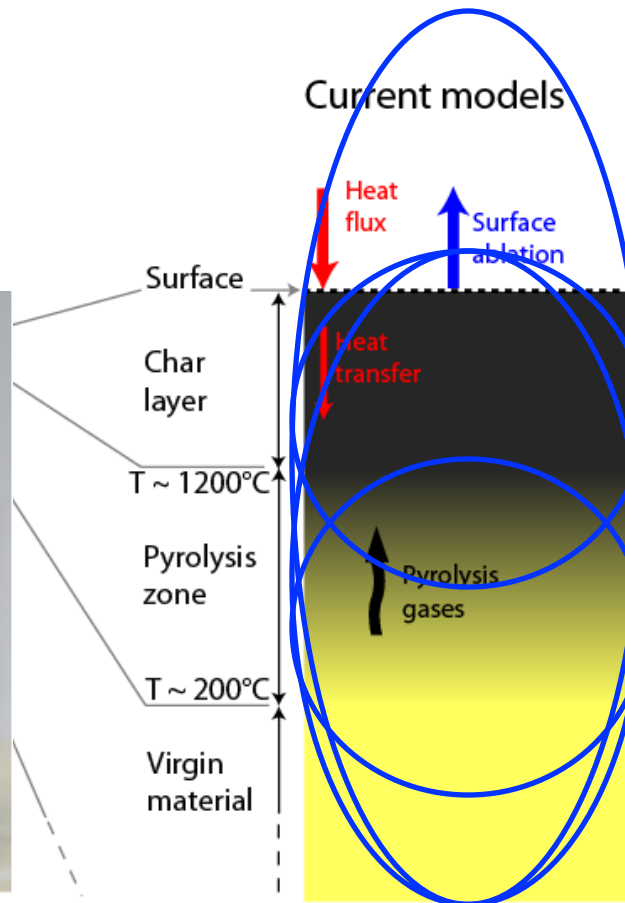




Building a model for PICA class



Core - Stardust TPS⁽¹⁾



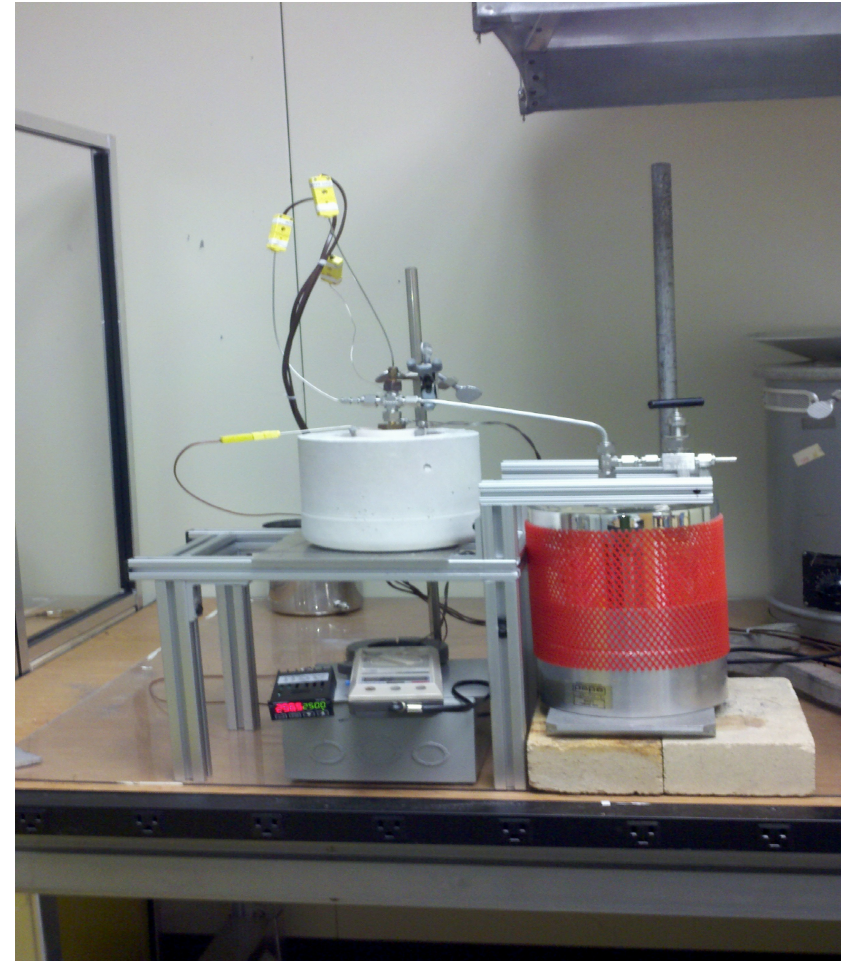
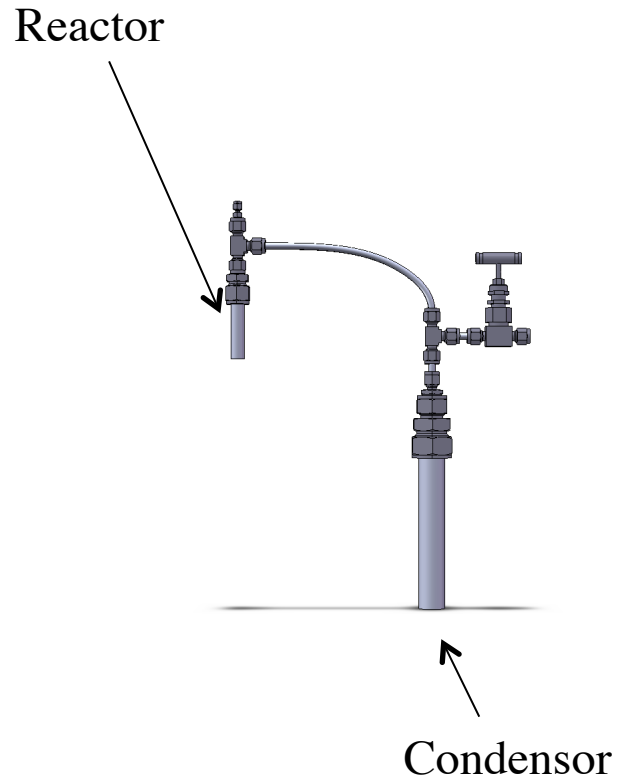
Current models

1. Pyrolysis analysis and modeling
2. Ablation analysis and modeling
3. Pyrolysis-ablation coupling
4. Flow Env. Material Res. coupling

[1] M. Stackpoole *et al.*, Post-Flight Evaluation of Stardust Sample Return Capsule Forebody Heatshield Material, AIAA 2008-1202



Pyrolysis experiments & modeling





Pyrolysis experiments & modeling

Detailed model of the pyrolysis

For $j \in [1, N_p]$ pyrolysis reactions

$$PFR_j \rightarrow \sum_{i=1}^{N_g} \gamma_{ji} A_i$$

where PFR_j is a fictive solid species of the phenolic formaldehyde resin (PFR).

$$\rho_m = \rho_{mv} - \delta\rho_p \sum_{j=1}^{N_p} F_j \xi_j$$

where

$$\frac{\partial_t \xi_j}{(1 - \xi_j)^{m_j}} = T^{n_j} \mathcal{A}_j \exp\left(-\frac{\mathcal{E}_j}{\mathcal{R}T}\right)$$

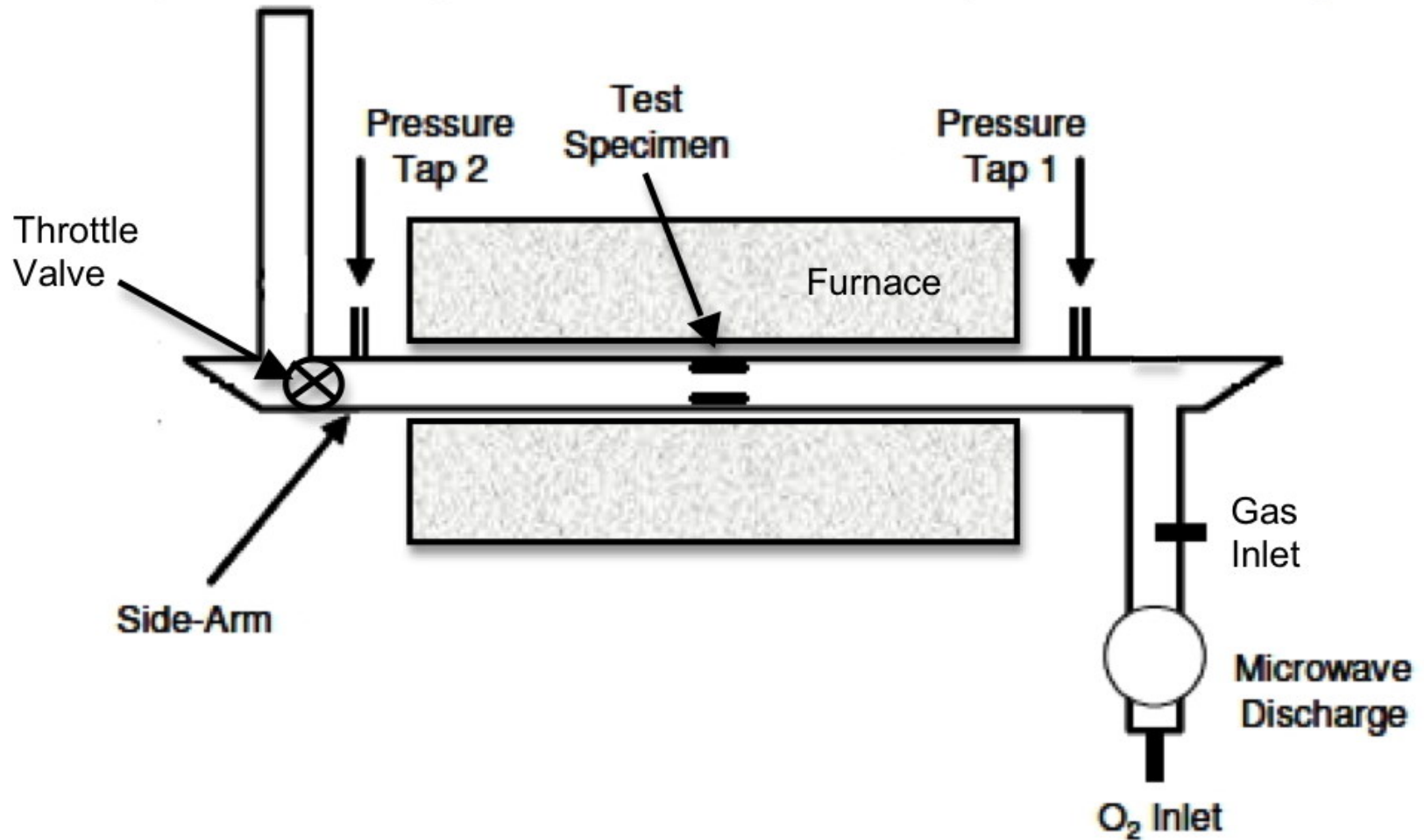
$$\langle \pi_i \rangle^g = \epsilon_m \delta\rho_p \sum_{j=1}^{N_p} [\partial_t \xi_j F_j \tilde{\gamma}_{ji}]$$

where

$$\tilde{\gamma}_{ji} = \frac{\gamma_{ji}}{\sum_{k=1}^{N_g} \gamma_{jk} \mathcal{M}_k}$$



Ablation Experiments & Modeling





Detailed model of the pyrolysis gas chemistry

Species conservation

$$\partial_t (X_i) + \partial_x \cdot (X_i \mathbf{v}_i^r) = \pi_i + \omega_i ; X_i = \frac{p}{RT} x_i$$

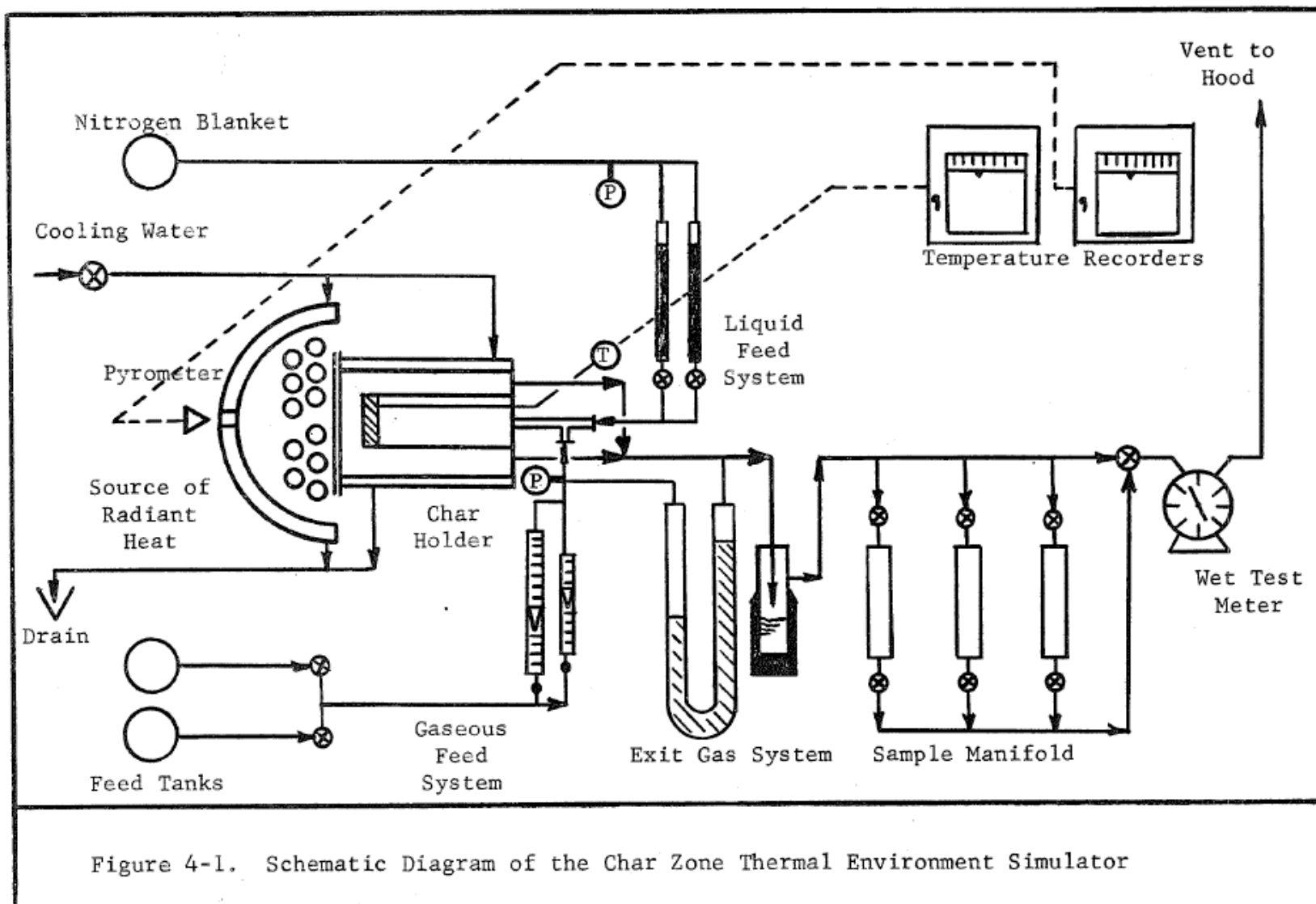
Finite-rate chemistry

$$\omega_i = d_t (X_i) = \sum_{r \in R} \left[(\nu_{ri}'' - \nu_{ri}') \left(k_r^f \prod_{j \in S} (X_j)^{\nu_{rj}'} - k_r^b \prod_{j \in S} (X_j)^{\nu_{rj}''} \right) \right]$$

Species and mass transport

$$\mathbf{J}_i^u = X_i \mathbf{v}_i^r = X_i (\mathbf{v} + \mathbf{V}_i^r) = \mathbf{J}_i^C + \mathbf{J}_i^D$$

Still missing: Heterogeneous chemistry





Summary

- Material performance tests (ArcJets, etc.) as well as basic laboratory testing campaigns are needed to advance material response models to match advancements in our ability to model the flow physics (i.e. the environment).
- High-fidelity models will enable fewer performance test campaigns and narrow the uncertainty in TPS designs.